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Validation of Integrated Thermal Power Measurement using Solution fuel STACY experimental data for modified STACY Performance Test

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1. Introduction

Japan Atomic Energy Agency (JAEA) is modifying the Static Experiment Critical Facility (STACY [1, 2]), which was a homogeneous system using a solution fuel, to a heterogeneous thermal neutron system consisting of the fuel rods and the light water moderator in order to contribute to the validation of the criticality calculations of the fuel debris in the Fukushima Daiichi Nuclear Power Plant.

The modification work of STACY is undergoing, with the intention to restart its operation in FY2023. Before the experimental operations, the modified STACY must be tested for various performance characteristics. Thermal power calibration is one of the tests.

In the STACY [3, 4] (solution fuel STACY), thermal power measurements for the power calibration were mainly conducted by sampling the fission products in the solution fuel after its operation because this method enabled us to measure directly integrated thermal power. The activation method using gold foils and wires was also conducted simultaneously to obtain supplemental data[5]. In the modified STACY, the fission product sampling method is not possible because we cannot take samples from the pellets sealed up in the fuel clad. And we should comply with a restriction of the installation position of the activation detectors, as set in the license of the safety authority. So that, we investigated the possibility of the activation method using few foil-shaped activation detectors for the thermal power estimation.

For this purpose, in this paper, we re-analyzed the experimental data obtained in the solution fuel STACY for the thermal power measurement by the activation method. The MVP [6] and PHITS [7] codes were adopted as analysis codes for neutron fluence and detector response calculations, respectively because the codes are widely used in each field. For nuclear data, JENDL-4.0 [7], which is used in many analyses, was also adopted. The re-analyzed results were compared with the data obtained by the fission product sampling method to validate the feasibility of the activation method using few activation foils.

2. Solution Fuel STACY Experiment

The solution fuel STACY consisted of a core tank and reflector pool tank as shown in Fig. 1 and 2. This work covered the experiments employing the 28-cm-thick, 69-cm-wide slab core tank (280T) and light water reflector. The fuel solution, which is uranyl nitrate, was fed to the core tank. It was submerged in the reflector pool tank. The reactivity was controlled by the solution fuel height in the core tank.

The experimental conditions are shown in Table I. The uranium concentration, the target core power, and the irradiation time were adjusted to values in the range of approximately 464 gU/L to 300 gU/L, 50-W to 200-W, and 10 min. to 55 min. respectively.

The activation foils, which were 20-μm thick, and 10-mm wide, were placed at eight positions as shown in Fig 1 and 2. The height of the activation detector position was varied with the critical solution level as shown in Fig.3. The activity of the activation foil was measured by the β-γ coincidence detector.

Table I: Experimental Conditions

Run	Uranium Conc. (gU/L)	Target Power (W)	Irradiation time (min)	Solution height (mm)
r106	428.8	50	50	428.5
r114	430.2	200	15	427.9
r117	430.8	200	10	426.8
r131	328.9	50	30	664.0
r140	313.3	60	55	814.2

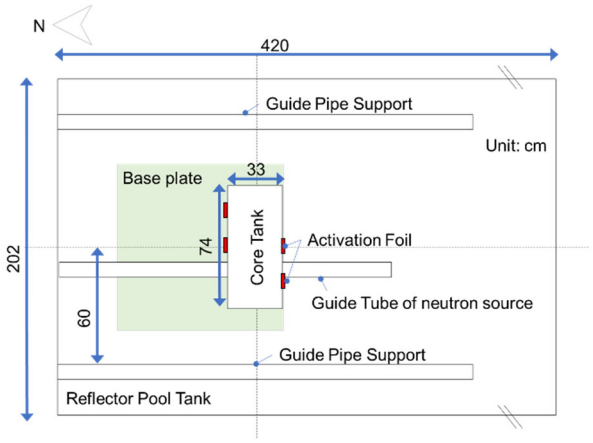

Fig. 1. Top view of the solution fuel STACY (280T) geometry.

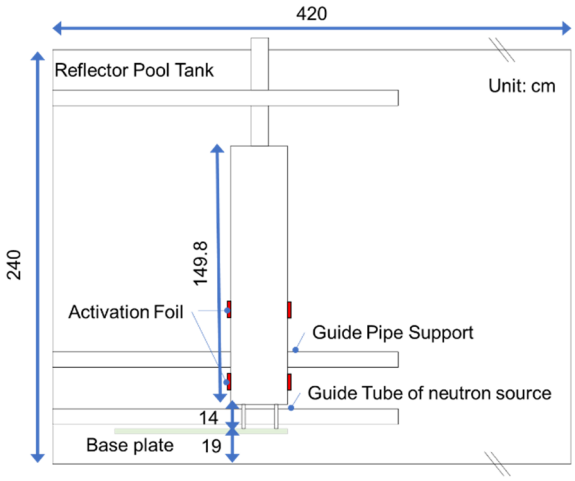

Fig. 2. Elevation view of the solution fuel STACY (280T) geometry.

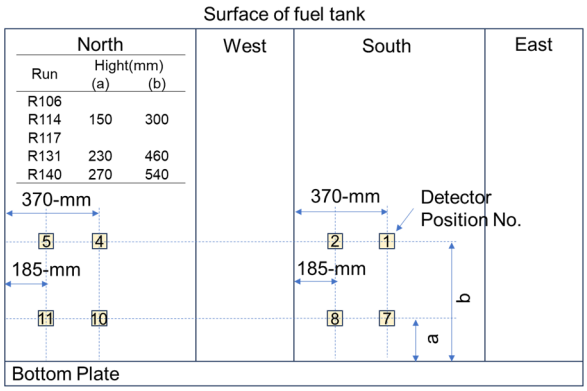

Fig. 3. Position of the gold foil activation detectors on the surface of the fuel tank

3. Analysis method

3.1 Activation method

Integrated thermal power P is obtained from the relationship between the fission number in the core and the neutron fluence at the detector position. The neutron fluence is derived from the ^{198}Au yield Y from (n,γ) reaction of ^{197}Au. The relationship between P and Y is described as Eq. (1):

$$Y = P \times R \times \Phi, \qquad (1)$$

where R is the response function of the activation detector in the unit source and Φ is neutron fluence at the detector position in unit integrated thermal power.

3.2 Neutron fluence and spectra

The neutron fluence and spectra were estimated by using the MVP code with JENDL-4.0. The calculation geometry was illustrated in Fig. 5, which consisted of the core tank and light water reflector. The detailed information of the solution type STACY is described as the LST-017 (Low enriched uranium, Solution, Thermal-017) in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [9].

The nuclide number density of the core tank and light water was defined to the same value used in the LST-016. The nuclide number density of the fuel solution was calculated in the same way shown in the LST-016.

The neutron fluence at the activation detector position was estimated by using the point estimator. The estimator is placed at the center of the position of each activation detector on the core tank. Only four estimators were modeled considering the positional symmetry of the activation detectors. The neutron spectra were tallied on all surfaces of the core tank with the surface cross estimator in order to reduce the calculation time. The calculations were conducted with 4.2×10^7 histories (2×10^4 histories pre-cycle, 2000 active cycles, and 100 skip cycles)

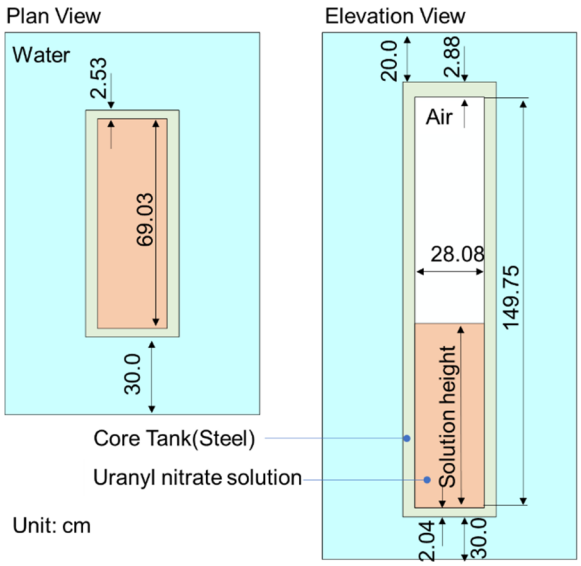

Fig. 5. Calculation geometry of solution fuel STACY (280T).

3.3 Response of activation detector

The response of the activation detector is described as Eq. (2):

$$R = \int N_{\mathrm{Au-197}}\, \sigma(E)\phi(E)dE, \qquad (2)$$

where $N_{\mathrm{Au-197}}$ is nuclide number density of ^{197}Au, $\sigma(E)$ is activation cross section of ^{197}Au, and $\phi(E)$ is neutron spectra. The response was estimated by the PHITS code with JENDL-4.0. The neutron spectra estimated in section 3.2 were used.

The calculation geometry was illustrated in Fig. 4. The gold foil (10-mm wide × 20-μm thick) was modeled. In the simulation by PHITS, the neutron having the estimated spectra was injected into the gold foil from a spherical shell source. The yield of ^{198}Au in the gold foil was estimated. The calculations were conducted with 10^7 histories.

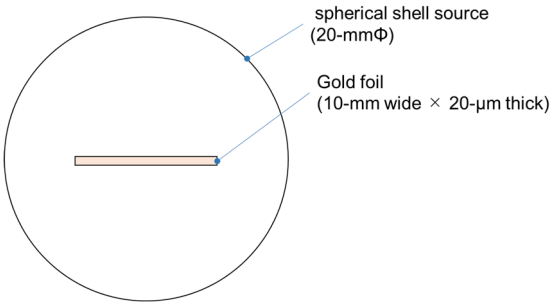

Fig. 5 Calculation geometry of response calculation in PHITS calculation.

4. Results and Discussion

4.1 detector position dependence

The results of the analysis of integrated thermal power at each activation foil in r106 are shown in Fig. 6 as an example. The uncertainty of the neutron fluence and ^{198}Au yield in the Monte Carlo calculation was taken into account as the error. The results were scattered beyond the range of the calculation uncertainty.

Figure 7 shows the relative standard deviations (RSD) of the result of the integrated thermal power in each experimental run number. The RSD was calculated as

$$\mathrm{rsd} = \sqrt{\frac{1}{n-1}\Sigma_{i=1}^{n}(x_i - \bar{x})}\,/\bar{x}, \qquad (3)$$

where n is the sample number, x_i is the result of integrated thermal power at activation foil i, and $\bar{x}$ is the mean of the results. The RSDs were at most or less about 6% in all experimental run numbers. The differences between the activation detector positions were considered to be small, although they were larger than the uncertainty of the calculation uncertainty. The effect of the detector position seems to be small in this method.

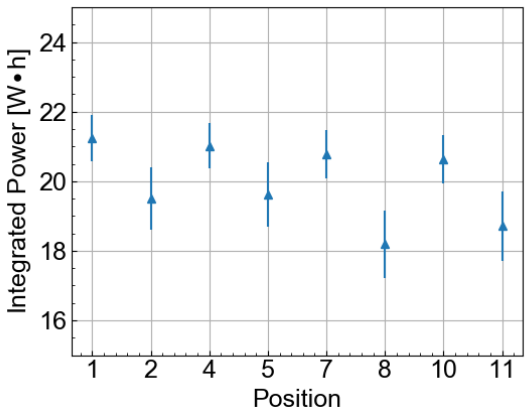

Fig. 6. Results of the analysis of integrated thermal power at each activation foil in r106.

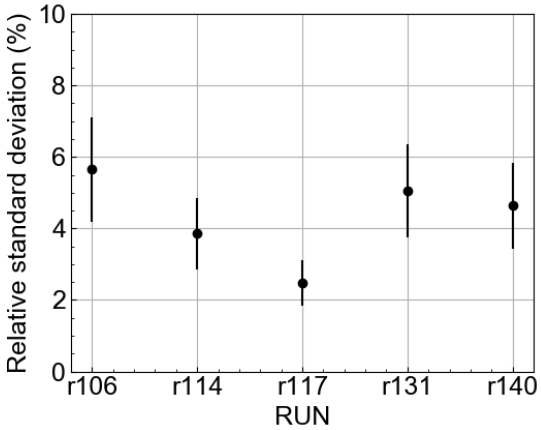

Fig. 7. Relative standard deviations of the results of the integrated thermal power in each experimental run number.

4.2 Comparison with fission product analysis

The average of the results was utilized for comparison with the results obtained by the fission product analysis [5], which contained an uncertainty of about 4%. The comparison with the fission product analysis indicated a good agreement as shown in Fig. 8. The ratio of the activation method to the fission product analysis is shown in Fig. 9. Most results of the two methods agreed within a 1-sigma uncertainty. The difference in the results by the two methods was at most 10%.

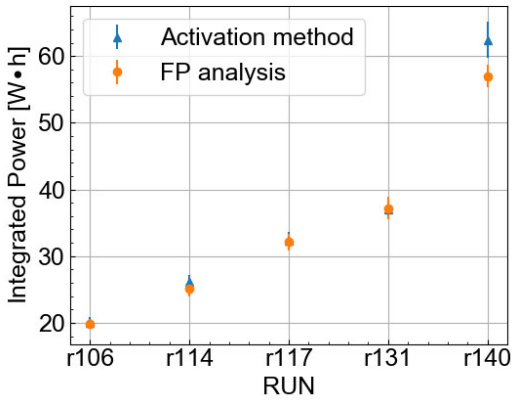

Fig. 8. Comparison between the results of the activation method and the fission product analysis.

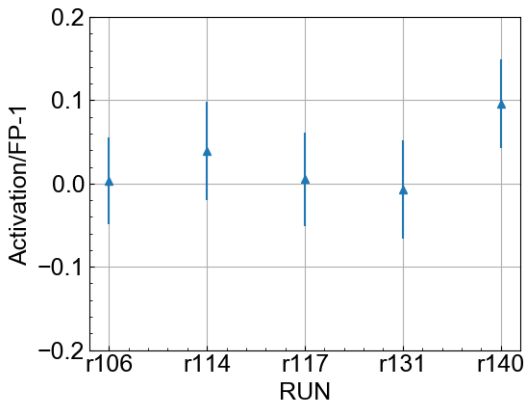

Fig. 9. Ratio of the activation method to the fission product method.

5. Summary and Conclusion

JAEA has been renovating the STACY from a homogeneous system using solution fuel to a heterogeneous system consisting of fuel rods and light water moderators with the goal of restarting the operation in FY2023.

In order to conduct integrated thermal power measurements for the performance test of the modified STACY, we re-analyzed the experimental data measured in the solution fuel STACY by using the activation method and validated its feasibility under the conditions with the limited number of activation detectors.

The re-analyzed results of the activation method by using MVP and PHITS with JENDL-4.0 indicated that the effect of the difference of the position between activation detectors was small enough and the results agreed with that of the fission product analysis within almost 10%. It is conceivable that the activation method could be adopted instead of the fission product analysis.

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